Appendix V: Molten Salt Reactor

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MOLTEN SALT REACTOR (MSR)

MSRs are liquid-fueled reactors that can be used for production of electricity, actinide burning, production of hydrogen, and production of fissile fuels. Fissile, fertile, and fission products are dissolved in a high-temperature molten fluoride salt with a very high boiling point (1400°C) that is both the reactor fuel and the coolant. The reactor can be built in large sizes with passive safety systems.

The use of a liquid fuel, versus the solid fuels of the other Generation IV concepts, creates potentially unique capabilities that are not achievable with solid-fuel reactors. The unique capabilities include:

- destruction of long-lived radionuclides without the need to fabricate solid fuels,
- a wider choice of fuel cycles (once through, waste burning, fissile fuel production) without major changes in the reactor design,
- full passive safety in very large reactors with associated economics of scale,
- limiting the radioactivity in the reactor core (accident source term) by on-line removal and solidification of the mobile fission products, and
- limited excess reactivity requirements in the core due to on line fuel management

However, these unique capabilities also imply a different set of technical challenges than other Generation IV concepts.

Two experimental MSRs have been built at ORNL and established the basic technology for the MSR. The first reactor was the 2.5 MW (t) Aircraft Reactor Experiment that in 1954 demonstrated peak operating temperatures up to 860°C. This was part of an effort to build a nuclear-powered military aircraft. This was followed in the 1960s by the Molten Salt Reactor Experiment, an 8 MW (t) reactor to demonstrate key features required for a molten salt breeder reactor (MSBR).

Today, the new interest in the MSR is its potential role for actinide management in the fuel cycle. Russian and OECD studies have identified the MSR as a potential component of a closed fuel cycle to efficiently burn actinides and thus offer the potential to reduce the long-term radiotoxicity of the wastes produced from production of electricity in other types of reactors. The use of liquid fuels avoids some of the technical difficulties (such as fuel fabrication) for burning actinides—especially the intensely radioactive higher actinides. There is a secondary interest in its use for hydrogen production because of the high-temperature capability. In Europe, there is the traditional interest in the MSR as a thermal-neutron breeder reactor. The different goals, combined with technical developments since the 1960s, are the basis for renewed interest in MSRs.

The MSR activities will be under the overall leadership of Oak Ridge National Laboratory. The MSR design cycle is shown in Figure 1

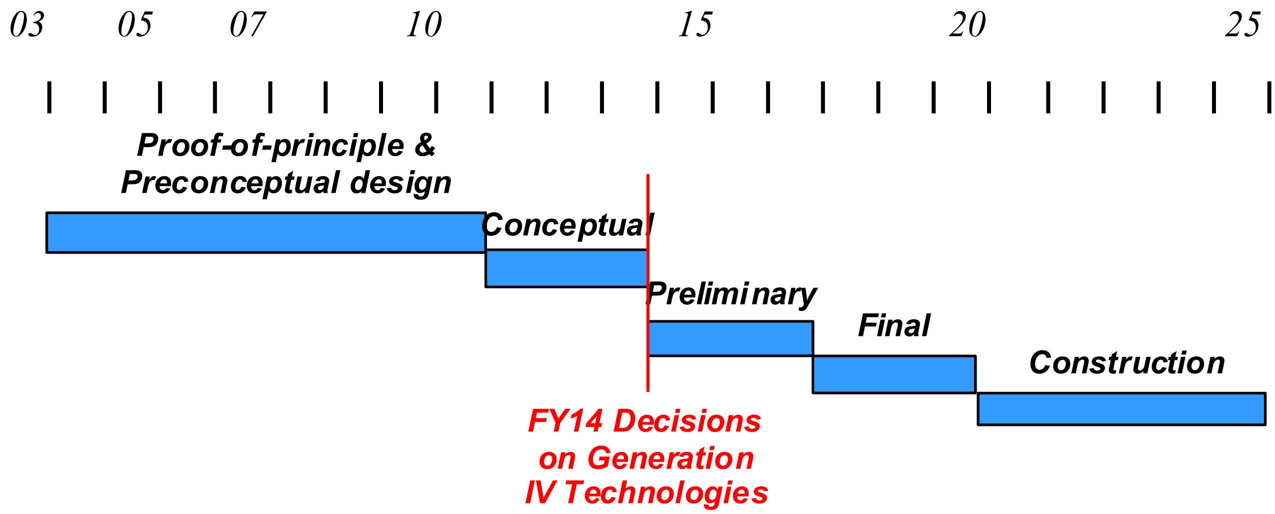

Figure 1 MSR Design Schedule

The development strategy for the MSR is based on two considerations. There is a massive technological overlap between an advanced MSR and the NGNP VHTR. Both are graphite moderated high-temperature reactors that share power cycles (Brayton helium), heat exchanger technology, and materials. Molten fluoride salts and helium are the only fluids that have been demonstrated as compatible with graphite and carbon-carbon composites. Many of the high nickel alloys required for the VHTR are also candidates for the MSR. In parallel, there is a renewed interest in MSRs in Europe with the European programs emphasizing molten salt chemistry and processing.

As a consequence of these ongoing synergistic programs, major advances in development and understanding of MSRs are expected to occur within the next decade with a modest investment of resources. This should enable the program to develop a credible understanding of the economics, capabilities to perform alternative missions (electricity, hydrogen, actinide burning, and fuel production), and issues associated with a modern MSR and thus provide the basis for a decision on whether to initiate a large scale developmental program with the goal of deployment.

1 SYSTEM DESIGN & EVALUATION

The goal of the system design and evaluation studies is to optimize system design for a modern MSR. Detailed conceptual engineering designs of large MSRs were developed in the 1960s. Since that time, there have been major changes in goals, regulatory requirements, and technologies. The impacts of these changes have not yet been integrated into the conceptual design approach to a next generation MSR. These earlier system studies will be used as the starting point to create an optimized modern MSR.

Coordination with other Generation IV concepts that use common technologies (graphite, Brayton power cycles, and compact heat exchangers in the VHTR) and international partners is critical to optimizing the resources available for MSR development.

1.1 Design Optimization

The objective of this work is to determine the characteristics and design parameters of a modern optimized MSR that updates the 30-year-old design established for the 1000+ MW(e) MSR. There are three major changes that must be incorporated into a modern MSR design. First, technologies developed since the 1960s have the potential to eliminate multiple technical issues associated with earlier MSR designs with major improvements in economics. These include three technologies being developed for the VHTR (helium Brayton power cycles that replace steam cycles, compact heat exchangers, and carbon-carbon composite components). Second, recent advances in remote operations, robotics, and controls offer promising approaches for the design of a modern MSR. Last, changing mission requirements will alter and may simplify plant design. Early MSRs were designed to maximize fuel production; that, in turn, required complex, high-capacity on-line salt processing. The actinide burner and hydrogen missions would not require online salt processing and generally simpler plant designs. Last, several new technologies may result in other plant simplifications.

1.2 Regulation

Liquid fuelled reactors use different approaches to reactor safety than solid fuelled reactors:

- draining the fuel into critically safe, passively cooled tanks if off-normal conditions occur,
- excess reactivity can be limited by online fuel processing and/or continuous fueling, and
- Fission produce source terms can be limited by online processing.

The current regulatory structure was developed with the concept of solid-fuel reactors. The comparable regulatory requirements for this system must be defined. Using current tools, appropriate safety analysis is required followed by appropriate research on the key safety issues.

1.3 Safety

The objective of this work is to obtain the information required to assure MSR safety. The critical safety requirement for a MSR is that the radionuclides remain dissolved in the molten salt under all conditions. The reactor size, design, and safety systems are dependent upon this property. There are two basic R&D tasks: (1) determine the limits of the solubility of trivalent actinides in candidate molten salts and (2) assure control of noble metal fission products in the primary system. New applications for MSRs, such as actinide burning, imply higher concentrations of trivalent actinides and noble metals in the salt than were used in the past and may require modification of the salt composition to assure solubility under all conditions. R&D is required to determine the trivalent solubility limits under these different conditions. Similarly, the behavior of noble metal fission products in the salt and their ultimate disposition is required. Under some conditions, fission product noble metals may plate out on heat exchangers resulting in high decay heat loads and limited equipment lifetimes.

2 MATERIALS

The major goals of the materials R&D are to identify materials with properties appropriate for MSR operating conditions including corrosion resistance, mechanical performance, and radiation performance. The primary materials of interest are the moderator (presently graphite), and the reactor vessel/primary loop alloy (presently a Ni-based alloy). It is also necessary to develop corrosion control and coolant monitoring strategies for the purpose of protecting the reactor vessel and primary piping alloys. The viability R&D will establish the primary candidate materials and control and monitoring strategies for further testing.

In addition to the historical experimental experience with molten salts at very high temperatures (~900°C) obtained for the Aircraft Nuclear Propulsion Program, an extensive materials development effort supported engineering code qualification for the MSBR to operate at 705°C. This temperature limit was largely due to the coupling required for steam cycle operations and did not represent a fundamental limit. Thus there is a natural base to build on to extend candidate materials for the higher temperature objectives of the Generation IV program. The MSR and VHTR both use graphite as a moderator and various carbon-carbon composites for multiple structural applications; consequently, graphite and carbon-carbon research will be coupled to the VHTR. Because the VHTR is currently pursuing Ni-based super alloys for reactor components, development of Ni-based alloys for molten salts should be coupled to the VHTR efforts.

2.1 Survey and Selection of Candidate Salt and Structural Materials

Candidate salts and materials will be selected based on literature survey, system design requirements, and investigation of materials usage in industrial application. In a MSR, the designer selects both the specific molten fluoride salt composition and the materials of construction. The demands of actinide burning may result in a choice of non-radioactive salt constituents that is different from previous applications. However, most of the work is not strongly dependent on the salt composition. Materials testing will take place over the range of temperatures, flows, and stresses expected in the MSR system

2.2 Irradiation Testing of Candidate Salt and Structural Materials

Candidate materials and salts will be irradiated under expected neutron spectrum conditions to extend the existing knowledge base to meet the Generation IV MSR requirements. Following irradiation, materials are screened for adequate mechanical performance, dimensional stability, and corrosion resistance.

2.3 Materials Modeling

Advanced, mechanistically based models for radiation performance will be developed. Developing materials modeling is expected to be a crosscutting activity.

3 ENERGY CONVERSION

The goal of the energy conversion R&D is to establish the technical basis for coupling helium Brayton cycles for electricity production and thermochemical water cracking cycles for hydrogen production to MSRs. These activities are expected to take place as part of an effort on Crosscutting Energy Conversion R&D.

3.1 Development of Heat Exchangers for Coupling to Energy Conversion Systems

Molten salts are candidates as the heat transfer fluid to transfer heat from the helium-cooled VHTR to hydrogen production facilities. This requires the development of high-pressure-helium to low-pressure-molten-salt heat exchangers. The same technology is required to transfer heat from the MSR to a helium power cycle—except the heat is transferred from the molten salt to the helium in the power cycle. Consequently, the R&D will be coupled to that of the Crosscutting Energy Conversion R&D.

3.2 Development of Multi-reheat Helium Brayton Cycle

The proposed MSR power cycle is an indirect, multi-reheat helium Brayton cycle. Most but not all of the components in this system are identical to the direct Brayton power cycles developed for other Generation IV concepts. Consequently, the R&D will be coupled to that of the Crosscutting Energy Conversion R&D. Fusion reactors may use the same molten salts as coolants (not fuelled) with the same power cycles. Thus, the R&D will also be coordinated with ongoing work in the DOE fusion program.

4 FUEL AND FUEL CYCLE

Molten salt fluorides are stable under irradiation; thus, there is no need for a classical solid-fuel development program. However, there are a variety of fuel cycle issues. Some are common to other reactors and their associated fuel cycles whereas some are unique to the MSR. Specifically, the system is a molten fluoride salt system with unique chemical issues not associated with other reactors. There is a need to develop a fluoride high-level-waste form and an integrated fuel recycles strategy. There have been major advances in separation technologies and proposals for highly innovative separation systems unique to fluoride salts. Because of the potential of these systems, preliminary exploration of these systems is appropriate. This activity is currently being coordinated in the AFCI program at the systems level. More detailed efforts will be required in the future.

Unlike many of the other Generation IV concepts, two proof-of-principle MSRs have been built and operated in the 1950s and 1960s. What has changed since then are (1) the goals for new reactor systems and (2) technological advances that may have fundamentally altered the relative competitive advantages of the MSR compared to other reactors. As a consequence, the program plan is directed toward development of a modern MSR in the context of (1) changes in goals and (2) changes in technology. ORNL is the lead laboratory. The University of California at Berkeley (UC-Berkeley) provides support. UC-Berkeley has the only university team in the United States that is examining MSRs and has programs examining the use of molten salts for cooling fusion reactors. This fusion work provides a critical link between MSR and fusion energy R&D.

5 FY 2004 WORK SCOPE

The FY 2004 activities, funded at the levels given in Table 1, include three tasks;

- The activity is to develop the definition of a modern MSR (key design features, choice of technologies, etc.). This involves working with other GenIV cross-cutting activities, the Advanced Fuel Cycle Initiative, and foreign groups on MSRs to understand the options for a modern MSR, the characteristics of each option, and developing a preliminary preconceptual design of a MSR. New technologies (particularly those being developed for the VHTR such as helium Brayton cycles, compact heat exchangers, and carbon-carbon composite structures), will fundamentally alter many of the key features of the traditional design.
- Interface with Generation IV International Forum to optimize effectiveness of R&D plan.
- ORNL will provide overall technical integration for MSR, including document control and project controls

The milestones for FY 2004 are listed below:

- Provide a report on a preliminary definition of a modern MSR.

Table 1 Summary of Level 4 Tasks for FY 2004 by Performer ($K)

Task	ORNL
Definition of a modern MSR	
Total	

6 FY 2005 WORK SCOPE

The FY 2005 activities, funded at the required level given in Table 2 include two tasks

- Initiate development of a baseline pre-conceptual design a modern MSR. This will couple European work on MSR reactor core designs with Generation IV studies on primary system heat exchangers, power cycles, and balance of plant systems. There is a strong coupling between the VHTR and proposed modern designs of MSRs. Both are (1) high temperature reactors, (2) use very similar [high-nickel] materials of construction, (3) have similar reactor core physics [graphite moderator], and (4) use a helium Brayton power cycle. Many of the major complications [tritium release, freezing of salts, etc.] of 1970s MSR designs were a consequence of coupling the MSR with a steam cycle. A helium gas-turbine power cycle is expected to greatly reduce multiple plant issues while increasing efficiency. In several other areas, three decades of technical progress will result in major changes from the 1970s designs. A detailed engineering design of a 1000 MW (e) MSR was developed in the 1970s. *This will be the starting point for the advanced design where changes will only be made in areas where new technologies have potentially a major impact on cost, safety, or environmental impact of the reactor.*

- Initiate development of a reactor core model of a MSR that defines for different goals the fuelling characteristics: different feeds [LWR plutonium and actinides, LWR higher actinides, etc.], continuous versus batch feeding, on-line versus off-line processing, etc. The model will provides the building blocks (black box) to couple the reactor with DOE and other system studies. Previous MSRs were designed to maximize breeding. This resulted in requirements for on-line fuel processing of the molten salt. Reducing this requirement may eliminate the need for on-line processing of fuel at the reactor and thus greatly simplify the reactor. For some cycles, no recycle of the fuel may be required.

The milestones for FY 2005 are listed below:

- Interim report that defines a preconceptual MSR design for electricity production
- Interim report defining major fueling options

Table 2 Summary of MSR Level 4 R&D Tasks for FY 2005 by Performer ($K)

Task	ORNL		UC-Berkeley		TOTAL	
	Required	Actual	Required	Actual	Required	Actual
Pre-conceptual Design						
Fueling/Core options						
TOTAL						

7 TEN YEAR PLAN

The high-level objectives of the MSR R&D program within the Generation IV programs are to:

- Establish a pre-conceptual point design for a modern economic MSR
- Assess tradeoffs between the reactor design and potential fuel cycle missions such as transmutation. Decisions for a second repository are likely to be made by 2009; thus, an understanding of these tradeoffs must be completed by 2007.

- Develop a cost estimate of a MSR. Economics is an absolute requirement for large scale deployment; thus, a preliminary understanding is required by 2010 when preliminary decisions on advanced reactors for fuel production are made.
- Establish potential of energy conversion systems to use molten salts as heat transfer agents and the ability to couple the MSR with energy conversion devices.
- Coordinate with ACFI Program to develop an integrated fuel cycle that couples with other reactors for actinide burning.
- Interface with Generation IV International Forum to optimize effectiveness of R&D plan

Major decisions (above) on the need for a second repository and down select of reactor options for fuel production divide the program into stages to support decisions. The activities for FY 2004 through FY 2013 are listed below:

FY 2004

- Define key design features for a MSR (such as power cycle, etc.).
- **Interface with Generation IV International Forum to optimize effectiveness of R&D plan.**

FY 2005

- Initiate pre-conceptual design a modern MSR.
- Initiate model of MSR fueling options.

FY 2006

- Complete initial pre-conceptual design a modern MSR with definitions of major design parameters and identification of major uncertainties. Major issues will be defined into two categories: (1) required for a viable reactor and (2) large impact on the economics. In many cases a particular technology can be made to work but a change in the technology would have a large cost impact.
- Complete initial model of MSR fuel cycle options.
- Start assessment, design, evaluation of MSR for actinide burning
- Initiate laboratory tests on materials (carbon-carbon composites and advanced nickel alloys) being developed for the VHTR that are projected to result in major improves the performance of the MSR (higher temperatures, compact heat exchangers with small volumes, etc.). Demonstrated materials are acceptable to about 750ºC.
- Initiate laboratory tests for control of noble elements dissolved in the salt.

FY 2007

- Second level trade studies on heat exchangers and power conversion systems.
- Complete actinide burning assessment including: integrated pre-conceptual MSR design with associated fuel processing facilities and multi-zone MSRs have two different fluids in the reactor core or a fluid fuel and solid targets for burning iodine and technetium. (Input to second repository study)

- Complete pre-conceptual design of a very-high temperature MSR with definition of major design parameters for hydrogen production.
- Initiate safety studies
- Continue laboratory tests on new materials (carbon-carbon composites and advanced nickel alloys) being developed for the VHTR that are projected to significantly improve the performance of the MSR—including testing at very high temperatures (1000ºC).
- Continue laboratory tests for control of noble elements dissolved in the salt.

FY 2008
- Follow-on actinide burning studies
- Initiate conceptual design, operation/maintenance, and costing study of a large MSR (AE). This will include evaluation of at least 2 sizes of reactors
- Initiate non-proliferation studies
- Complete initial safety studies
- Continue laboratory tests of materials
- Continue laboratory tests for control of noble elements dissolved in the salt.

FY 2009
- Complete conceptual design, operations/maintenance, and costing study
- Complete non-proliferation study
- Initiate commercialization study
- Complete licensing study
- Special studies of issues identified.

FY 2010
- Develop integrated development and commercialization plan
- Start design of a MSR test loop in research reactor (probably ATR). Test loop includes the molten salt and fuel with appropriate cleanup and laboratory facilities (major test facility)
- Continue laboratory tests of materials
- Initiate studies and tests for key uncertainties

FY 2011-2013
- Implement development and commercialization plan
- Define and initiate design of other test facilities
- Multiple trade studies to optimize design

The milestones of the ten-year plan are as follows:

FY 2004
- Define key design features for a MSR (such as power cycle, etc.).

FY 2005

- Initiate pre-conceptual design a modern MSR.

FY 2006

- Complete pre-conceptual design a modern MSR.
- Complete initial model of fuel cycle options.
- Complete initial screening of new materials in molten salts.

FY 2007

- Complete actinide burning assessment.
- Complete pre-conceptual design of a very-high temperature MSR.
- Complete initial assessment and down select of options for control of noble elements dissolved in the salt.

FY 2008

- Initiate conceptual design and costing study of a large MSR (AE).
- Complete initial system safety study
- Complete initial loop corrosion tests on new materials

FY 2009

- Complete conceptual design, operations/maintenance, and costing study
- Complete non-proliferation study
- Complete licensing study

FY 2010

- Develop integrated development and commercialization plan
- Start design of a MSR test loop in research reactor (probably ATR). Test loop includes the molten salt and fuel with appropriate cleanup and laboratory facilities (major test facility)

FY 2011-2013

- To be defined

The major deliverables are supported by funding as shown in Table 3.

The cost estimates for this required R&D scope between FY2006 and FY2013 is shown in Table 3.

Table 3. Cost estimate for required scope to conclude viability demonstration by 2010 and perform higher-priority R&D after technology selection ($M).

Task	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total
Materials									
Fuel and Fuel Cycle									
System Design and Evaluation									
Energy Conversion									
TOTAL									

8 PERFORMANCE MEASURES FOR FY 2004 AND FY 2005-TO-FY 2013

FY 2004
Complete a pre-conceptual design of a modern MSR (excludes fuel cycle).

FY2005 to FY 2013
See milestones.